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Aging Mitigation and Improved Programs for Nuclear Service Diesel Generators

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Operated by
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ABSTRACT

Recent NRC sponsored aging research work on nuclear service diesel generators has resulted in a recommendation that an improved engine management program should be adopted for aging mitigation and reliability improvement. The center of attention should be to ensure diesel-generator operational readiness. This report emphasizes a "healthy engine concept" and recommends parameters to be monitored to determine engine condition. The proposed program and approach recommended in this report represent balanced management where diesel generator testing, inspections, monitoring, trending, training, and maintenance all have appropriate importance.

Fast-starting and fast-loading tests of nuclear service diesels causes very rapid wear of certain engine components. This report documents this aging and wear mechanism and recommends ways to largely eliminate this unique aging stressor. Current periodic intrusive maintenance and engine overhaul practices have been found to be less favorable for safety assurance than engine overhauls based on monitoring and trending results or on a need to correct specific engine defects. This report recommends that the periodic overhaul requirements be re-evaluated.

Diesel generator research on aging and wear is sponsored by the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research. The research reported in this report was conducted by Pacific Northwest Laboratory (PNL), which is operated for the Department of Energy by Battelle Memorial Institute.

SUMMARY

NRC PROGRAM IDENTIFICATION

The Nuclear Plant Aging Research (NPAR) Program was established by the NRC's Office of Nuclear Regulatory Research, Division of Engineering, Electrical and Mechanical Engineering Branch, to evaluate the effects of aging on selected safety-related components, systems and support systems. It is addressing how the aging process may change current safety margins of key components in safety-related systems and how aging degradation can initiate failure.

The NPAR study of diesel generator aging was performed in two phases. In Phase I, plant operating experience and data were used to produce a new data base related to aging, reliability, and operational readiness of nuclear service diesel generators. Phase II is chiefly concerned with aging mitigation measures.

PNL DIESEL GENERATOR MANAGEMENT PROGRAM

This report proposes a management, testing, and maintenance program for emergency diesel generators that was developed as a product of Phase II of this effort. The proposed program would lead to three expected results: 1) the reduction of several of the stressors identified in Phase I that have been shown to accelerate aging of diesel generators, 2) an improved state of reliability and operational readiness, and 3) improved confidence in the future availability and reliability of the diesel-generator.

The proposed new program would integrate testing, inspection, monitoring, trending, maintenance, and other elements for a better diesel generator aging mitigation approach. The new recommended program is further described in Section 5.0. The more important elements of the new proposed program are summarized in the following paragraphs.

An improved diesel-generator testing program including slow starting and loading would induce little aging effects in the emergency diesel-generator. By contrast, the current fast starting and loading testing requirements can produce substantial harm and significant aging effects through the production of large mechanical and thermal stresses, inadequate lubrication during initial acceleration, high rotating and sliding pressures, overspeeding, etc. During the monthly testing program, adequate data should be collected for about 30 engine operating parameters that could indicate degrading performance or an impending component failure. These parameters of interest are detailed in Appendix A of this report. For many important components such a program could then detect approaching performance failure and allow orderly repair. Monitoring and trending will not be able to detect all degraded

performance, of course, but the deterioration that will be detected is significant for aging and reliability concerns. These recommended tests are presented and further discussed in Section 5.2.

Condition monitoring and trending is an important development to show the possible presence of long-term component or system degradation. This activity should detect many potential component/system failures before the system actually fails. Cost and safety benefits would accrue from the avoidance of both equipment damage and unscheduled downtime by anticipating these failures and providing timely repair/maintenance. The monthly test program should ensure that the operating parameters listed in Appendix A are within their maximum and minimum limits as applicable. However, it is not necessary to trend every parameter for effective results. Deviations from normal engine conditions towards either maximum or minimum allowed limits need not be trended until perhaps fifty percent of the allowed range of values is exceeded. Obviously, the chief safety concern is to operate the diesel generator within the manufacturer's recommended values. When a limiting value is being approached the utilities should trend the approach to avoid failures and schedule repair before limits are exceeded.

Several recommendations were developed regarding maintenance procedures and training. One important recommendation is that teardown of the diesel engines solely for the purpose of inspection should be avoided unless there is a definite indication that its operation is degraded or there is an impending component failure based on performance data trends. Analyses of failure data have also been performed by the U.S. Navy and the airline industry which show a definite average, short-term adverse effect of such teardowns on the engine reliability.

Understanding of the governor, as well as the engine/generator, must be developed by providing the maintenance staff with adequate training and motivation. The staff associated with each plant should be given training equivalent to that offered by the specific engine and governor manufacturer that supplied the engines for that plant.

Finally, it was recommended that engine inspections and preventive maintenance be increased to mitigate the aging and wear results of the vibration stressor. This maintenance should focus on the engine or instrumentation mounted on the engine or the engine skid. Normal engine vibrations have a known and severe influence on control system instruments and their calibration. Vibration cannot be eliminated, but its effects can be mitigated by keeping fasteners/fittings tight and by frequently recalibrating instrumentation subject to this vibration.

EDG MISSION ANALYSIS AND RECOMMENDATIONS

The role of the diesel generator safety mission related to the aging study is reviewed in this report in Section 3. To respond to a large-break LOCA event with a corresponding loss of all offsite power, a diesel generator needs to start promptly and deliver its full emergency loads until the emergency is over. This mission profile is the basis and focus of current regulatory requirements and testing. With over 1000 reactor years of operation in U.S. regulatory history without a large-break LOCA event for primary water containment and with the recent Criterion 4 (leak-before-break) rulemaking, it may be concluded that the true mission envelope for the diesel-generator may be redefined with consequential benefits.

For a loss of offsite power, with or without a small-break LOCA event, the related needs for emergency electrical power and the diesel mission profile are much less stringent. In this case, the need for power is extended to about 5 minutes or so and the emergency power level needs are reduced, but the time duration for emergency power may remain for several days. Thus, in summary it appears that the prevention of station blackout is the most realistic mission envelope.

The most probable risk-responsive requirements for the diesel-generator mission are very high reliability with the durability to produce power over 3 to 4 days until the emergency passes and the reactor cooling requirements rapidly drop off. This is essentially the "station blackout" issue. But, accepting this mission envelope for the diesel-generator system also results in the reduction in aging degradation of many important engine components through less harmful test requirements. A more practical mission envelope for the diesel generator system appears to be:

- total duration - 2 to 3 days
- diesel start and load time - within 5 minutes
- power level - less than calculated full load (core and containment sprays not needed). Also, by usual design practice, less than the engine nameplate rating by a conservative margin.

In consideration of the mission analysis it appears that safety concerns are better served by testing the engines for reliability rather than maximum starting accelerations and very rapid loading which it seems is not needed.

REGULATORY IMPLEMENTATION

The NPAR aging study was originally intended to develop research for NRC consideration related to potential safety problems caused by the aging process. General applications of the study results were expected to be used for 1) diesel reliability improvement, 2) plant technical specification modification, 3) improvement of resource applications by the NRC and the utilities, and 4) development of specific research information needed to change some regulatory requirements. All of these end uses of the research have been accomplished or are under active consideration. Collectively, the safety implications of these changes and research recommendations are important.

Current regulatory requirements for fast-start testing, fast engine loading, and overload testing are being reconsidered by the NRC. In association with certain nuclear plant technical specifications, these current requirements may lead to greater future safety problems and unreliability. Regulatory guide requirements for routine testing have been proposed to include slow-start testing, slower engine loading, and diesel overload testing objectives that can be supported by the study results.

NRC Regulatory Accomplishments

In response to various industry proposals, research information, and NRC staff initiatives much has been accomplished in the area of diesel-generator aging and reliability. The current status includes much activity and the NRC staff accomplishments reported in this summary may soon be out-of-date.

Based on various historical conditions the NRC staff has issued Regulatory Guide 1.155, "Station Blackout" in August, 1988 which identifies a need for a reliability program. This reliability program for emergency diesel generators is intended to maintain and monitor reliability levels selected for compliance with the Station Blackout Rule 10 CFR 50.63 (6/68).

Regulatory Guide 1.9, Revision 3, "Section, Design, Qualification, Testing, and Reliability of Diesel GEnerator Units Used as Onsite Electric Power Systems at Nuclear Power Plants" is in the final NRC approval process and is expected to be issued in 1989. It integrates into a single guide material previously addressed in Regulatory Guides 1.108, 1.9 Revision 2 and Generic Letter 84-15. Regulatory Guide 1.108 will be withdrawn after the issue of Regulatory 1.9, Revision 3.

A Research Information Letter was issued by the NRC during 1989 which recommends a balanced program of testing, inspection, monitoring, trending, and maintenance for aging mitigation and for assuring diesel generator operational readiness. The recommended guidelines for this reliability program follow the results and recommendations included in this report. The NRC in November 1988 issued a report to the NRC staff proposing changes to the standard technical specifications including many examples obtained from the NPAR diesel generator task.

Proposed NRC Actions

Regulatory Guide 1.137, Fuel-Oil Systems for Standby Diesel Generators, has not been revised since October 1979. Aging considerations for the system and the fuel oil contents needs to be addressed. The scope of the changes recommended are outlined in Section 7.1 and include reducing the needed fuel oil storage to a 3 to 4 day supply, defining tank lining materials, addressing independence and redundancy guidelines, and reconsideration of the specifications for stored fuel to include usual and expected aging changes.

The standard technical specifications including diesel generator specific issues needs to be addressed. The research information gathered in the NPAR Diesel program suggests that current technical specifications are not always conservative nor effective. In particular, those related to fast engine starting and loading, frequent sensor calibration, engine startup during abnormal plant conditions, frequent starts and special test requirements need to be carefully evaluated.

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1.0 INTRODUCTION

Commercial nuclear power stations use large diesel generators to supply Class 1E emergency standby power to support the operation of emergency safety and plant protection system loads. During a loss of power to the emergency plant buses, the diesel generators must provide backup power to operate critical reactor safety equipment. Generally, each nuclear unit is provided with two diesel generators, each rated at 3,000 to 10,000 horsepower.

The potential serious consequences of the failure of these diesel generators to produce power following a loss of off-site power have caused considerable regulatory attention to be directed at their reliability. Since aging of the diesel generators and their associated systems could contribute to their failure (Davis et al. 1985), the U.S. Nuclear Regulatory Commission (NRC) has included the consideration of diesel generators in the Nuclear Plant Aging Research (NPAR) Program.

The NPAR program was established by the NRC's Office of Nuclear Regulatory Research, Division of Engineering, Electrical and Mechanical Engineering Branch, to evaluate the effects of aging on selected safety-related components, systems and support systems. It is addressing how the aging process may change current safety margins of key components in safety-related systems and how aging degradation can initiate failure. The goals of the NPAR program are to:

- identify and characterize aging and service wear effects which, if unchecked, could cause degradation of systems, components, and civil structures and thereby impair plant safety
- identify methods for inspection, surveillance, monitoring, and evaluation of the residual life of structures, systems, and components and civil structures that will assure a timely detection of significant aging effects before a loss of safety function develops
- evaluate the effectiveness of operations, maintenance, repair, and replacement practices in mitigating the rate and extent of degradation caused by aging.

The NPAR study of diesel generator aging was performed in two phases. In Phase I, plant operating experience, data, expert opinion and statistical methods were used to produce a new data base related to aging, reliability, and operational readiness of nuclear service diesel generators. Phase II is chiefly concerned with aging mitigation measures. Phase I of this program has been completed and the results of assessments of wear and aging experience have been published (Hoopingarner et al. 1987, Vol. 1 and 2). Methods for testing and aging mitigation (Hoopingarner et al. 1988) have been published as part of the Phase II work.

The purpose of this report is to describe a proposed management, testing and maintenance program for emergency diesel generators that was developed as a product of Phase II of this effort. The proposed program would lead to three expected results: 1) reduce stressors identified in Phase I that lead to accelerated aging of nuclear service diesel generators, 2) provide an enhanced state of reliability and operational readiness, and 3) provide improved confidence in future diesel-generator availability.

The research reported in this document was conducted by the Pacific Northwest Laboratory (PNL), which is operated for the Department of Energy by the Battelle Memorial Institute.

1.1 BACKGROUND

The aging of a nuclear service emergency diesel generator may be envisioned as the cumulative deterioration of components and supporting systems. This aging can lead to a loss of reliability to start, assume the defined emergency loads, and once started to continue to run for the duration of the emergency or, in case of routine operational verification testing, the duration of the test. This deterioration may be the result of wear, metal fatigue, oxidation, bacterial action, vibration, accumulation of deposits, maladjustment, etc., and it may occur gradually over months and years, or relatively rapidly over a shorter period.

The necessity of achieving and maintaining a high level of diesel generator reliability has long been recognized as an essential element of nuclear plant safety and has received considerable regulatory attention. During the period from 1959 to 1973, diesel generator availability was assured by testing conducted on a monthly basis and during refueling. In 1975, a report by the U.S. Atomic Energy Commission (AEC) evaluated diesel generator failures being experienced during this period and concluded that <u>one</u> specific problem was dominant and identified it as the <u>starting</u> of the engine (AEC 1975). This experience led to the general perception that if a diesel generator could start, it would likely continue to accept load and continue to operate reliably.

In 1977, Regulatory Guide 1.108 (Rev. 1) was issued and it defined a routine testing schedule that related the testing frequency to the number of failures being experienced. This guide requires that the diesel generators be "fast, cold" started at intervals of at least 31 days. If two failures are experienced in the last 100 valid tests, then the maximum test interval is decreased to 14 days. If three failures are experienced in the last 100 valid starts, the maximum test interval is further decreased to 7 days. Finally, if four or more failures are experienced in the last 100 valid tests, starting tests must be performed at least every three days. The requisites for a valid test are delineated in the guide. The thrust of this requirement was to encourage utilities with diesel generators with high failure rates to make major improvements to avoid the high costs of frequent starting tests.

"Fast, cold" starting refers to plant technical specification requirements that the engine be started within 10 to 12 seconds from ambient conditions and fully loaded within 30 to 45 seconds. In general, if a licensee uses a keep-warm system for either the jacket cooling system or the oil system or both, the thermal condition provided by these systems becomes a part of the "ambient condition." The 10 to 12 second start time and 30 to 45 second full-load time was not specified in Regulatory Guide 1.108 but was determined from fuel cladding temperature calculations defined in 10 CFR 50, Appendix K. These requirements were then made a part of each plant's technical specifications.

With Regulatory Guide 1.108 requirements in place and with some industry changes in practice, starting failures were no longer dominant, and failures such as fatigue and wear of engine components from fast start testing were observed. In 1982, a summary of diesel generator performance presented to the Advisory Committee for Reactor Safeguards (ACRS) recommended that 1) routine test starts on a 3-day frequency should be eliminated, 2) testing should be focussed on unreliable diesel generators and major repair action should be pursued, rather than just more testing, and 3) when a failure has occurred, an initial test of redundant units should be conducted with a followup test about every 3 days to provide increased assurance that a new failure has not occurred (Beard 1982).

NUREG/CR-2989 reported an investigation of diesel generator reliability based on data from the 1976 to 1980 period and concluded that their average reliability was 0.975. Human errors and hardware related common mode failures were observed to be 0.2%. No one type of equipment failure was dominant. The most frequently observed failures were control and logic problems (14.7 %) followed by governor failure (12.3 %). Several actions were recommended to improve diesel generator reliability including 1) periodic governor maintenance, 2) performance of root cause analyses, 3) adding corrosion inhibitors to jacket cooling water, 4) upgrading operating/maintenance procedures, and 5) installing an additional diesel generator unit.

The NRC recognized the possibility of detrimental effects of the very testing that was originally meant to assure the diesel generators' reliability. In December of 1983, Generic Letter 83-41 was issued which requested licensees to provide information related to potential detrimental effects of "fast, cold" starts. This letter was followed by Generic Letter 84-15 in July 1984 which described changes in requirements to improve diesel generator reliability. This action requested that the licensees take action to reduce "fast, cold" starting tests and encouraged them to propose technical specification changes. The generic letter also described a goal-oriented reliability program developed by the staff and invited licensee comments on this program.

Recently, a major change has been made to 10 CFR 50, General Design Criterion 4, which accepts leak-before-break analysis and detection for large bore primary system piping. This change could result in a relaxation of emergency diesel generator start time, but new criteria have not yet been promulgated. Studies by the Electric Power Research Institute (Muralidharan 1986 and Schwartz 1988) and others have indicated that the emergency power requirements are on the order of 1 to 2 minutes for a loss-of-coolant accident (LOCA) with a simultaneous loss of off-site power and on the order of 5 minutes or more for a loss of off-site power without a LOCA.

Although NRC is moving away from frequent fast-starting requirements and allowing some "slow-start" testing, the technical specifications for the majority of U.S. nuclear power stations still call for fast, cold starting, exclusively, for monthly tests of diesel generators. In addition, at the present time, most stations have not installed the necessary hardware modifications to permit both slow-start testing and fast-start response of the diesel-generator system.

The historical approach taken by NRC for assuring diesel generator reliability had the objectives of developing statistical data on the past reliability of the tested units and providing incentives to licensees to perform major mechanical improvements to reduce the expense of performing frequent testing. However, it provides no information on the long-term degradation of the performance of components and related systems which could lead to future failures and which could be corrected before an actual failure occurs or before a unit's reliability is compromised. The detection time to statistically determine unacceptable performance deterioration is considered to be excessive.

In response to these historical conditions, the NRC staff has acted by the issue of Regulatory Guide 1.155, "Station Blackout" in August, 1988 which identifies a need for a reliability program. This reliability program for emergency diesel generators is designed to maintain and monitor reliability levels selected for compliance with the Station Blackout Rule 10 CFR 50.63 (6/68).

Regulatory Guide 1.9, Revision 3, "Section, Design, Qualification, Testing, and Reliability of Diesel Generator Units Used as Onsite Electric Power Systems at Nuclear Power Plants" is in the final NRC approval process and is expected to be issued in 1989. It integrates into a single guide pertinent guidance previously addressed in Regulatory Guides 1.108, 1.9 Revision 2 and Generic Letter 84-15. Regulatory Guide 1.108 will be with-drawn after the issue of Regulatory Guide 1.9, Revision 3 is consistent with industry guidance contained in NUMARC-8700, Appendix D and with the recom-mendations contained in this report.

Many prior operational and testing practices deleterious to engine reliability and life, such as cold fast starts, have been deleted. The development of Regulatory Guide 1.9, Revision 3 has utilized information obtained through the NPAR Program, Diesel Generator Task.

2.0 SUMMARY OF THE NPAR DIESEL GENERATOR AGING STUDY

Emergency diesel generators were included in the NPAR program because of 1) the safely implications of the failure of the diesel generators during an emergency situation (Davis et al. 1985), 2) the correlation of risk and aging trends (Davis et al. 1985), and joint recommendations of several NRC offices including Nuclear Reactor Regulation (NRR), Nuclear Regulatory Research (RES), Inspection and Enforcement (IE), and Analysis and Evaluation of Operational Data (AEOD).

For the purpose of this study, subsystems supporting the emergency diesel generators were included along with the diesel generators themselves, because together they form a complex overall system which will fail to perform its safety function if any component functions less than adequately. Specific components and subsystems considered as part of the diesel generator system include the 1) diesel engine, 2) governor, 3) starting system, 4) turbocharger and intake combustion air system, 5) cooling system, 6) fuel oil storage and delivery system, 7) lubricating oil system, 8) exhaust system, 9) generator, 10) exciter and voltage regulator system, and 11) instrument and control system. Not included in this study were the 1) remote control and surveillance system, 2) external electrical power supply system supplying ac and dc power to various systems, prewarming system and the pre-lube system, and 3) Class 1E electrical distribution system.

2.1 SCOPE AND METHODOLOGY

In the NPAR Program emergency diesel generator study, diesel generator systems as defined in Section 2.0 were evaluated to 1) determine which components and subsystems were subject to aging, how they failed, and with what frequency, 2) determined the adequacy of surveillance, inspection, and trending methods, and 3) assessed the role of maintenance and other industrial practices in resolving aging effects. The overall objective of this study was to provide information to assist the regulatory organizations and plant operators to understand the role of aging in emergency diesel generators.

The study to date was performed in two phases. Phase I, which was completed and provided general background material for this report, was concerned with defining which diesel generator system components fail and the principal causes of the observed failures. This work was based on failure information on components within the defined system boundary obtained from the Nuclear Plant Reliability Data System (compiled by the Institute for Nuclear Power Operations), Licensee Event Reports, Nuclear Power Experience (Stoller 1982) and Emergency Diesel Generator Component Tracking System (compiled by TDI Owners Group). These data were analyzed statistically and reviewed subjectively by a panel of diesel experts to determine which components were most susceptible to aging, the principal causes of these failures, and the maintenance procedures that either contributed to failures or prevented them. The panel of diesel experts was made up of recognized industrial experts in diesel engine design, application, installation, operation and maintenance. Current inspection, surveillance, and maintenance practices were reviewed to determine any relationships between these practices and the type and number of failures being encountered.

Phase II of this study is underway and is the basis for this report. The principal objective of Phase II is to develop information and recommendations to assist regulatory organizations and plant operators to assure maximum diesel generator reliability. This activity will be performed with interaction with the NRC Staff, industry, and code and standards committees.

2.2 TECHNICAL SAFETY ISSUES AND RESEARCH RESULTS

This report is based on the results of the Phase I activity of the Diesel Generator Aging Research Program which is reported in detail in (Hoopingarner, et al 1987). The principal issues addressed in Phase I included the following:

- failures which occur most often in emergency diesel generator systems
- subsystems and components involved in these failures
- fraction of the failures due to aging
- observable aging trends
- important aging stressors
- potential corrective actions and mitigating measures.

About 500 reported diesel generator failure incidents occurring from 1965 to 1984 were randomly selected from each of the 4 data sources listed in Section 1.1 to form a representative data base which resulted in 1,984 cases of diesel generator system failure. Diesel engines tabulated in this representative data base included those manufactured by ALCO, Allis Chalmers, Caterpillar, Cooper Bessemer, Fairbanks Morse, Electromotive Division of General Motors, Nordberg, Transamerica Delaval, and Worthington.

2.2.1 Aging Related Failures and Their Causes

Systems and components that contributed most to all diesel generator failures are summarized in Table 2.1. The most significant causes of failure are summarized in Table 2.2. Of the 1,984 incidents of diesel generator failure in the representative data base, 1,064 were judged to be related to some form of aging. Of these 1,064 aging failures, 629 resulted in the loss of function of the diesel generator system or impaired its reliability. Systems and components identified as being major contributors to this group are shown in Table 2.3. The principal causes of failures that resulted in loss of function or impairment of reliability are summarized in Table 2.4.

TABLE 2.1. System and Components Contributing Most to Diesel Generator Failures

Systems and Components	Percent of All Failures
Instrument and Control Systems	25
Governor	10
Sensors	3
Relays	2
Startup Components	2
Fuel System	11
Piping on Engine	3
Injector Pumps	2
Starting System	10
Controls	3
Starting Air Valve	2
Starting Motors	2
Air Compressor	1
Switchgear System	10
Breakers	3
Relays	2
Instrument and Controls	1
Cooling System	9
Pumps	2
Heat Exchangers	2
Piping	2
Lubricating System	7
Heat Exchangers	2
Pumps	2
Lube Oil	1
Other Systems	28

TABLE 2.2. Overall Causes of Diesel Generator Failures

Failure Cause	Percent of All Failures
Poor manufacture or construction quality control	22
Adverse conditions - vibration, shock	17
Human error - maintenance	13
Adverse environment - dust, humidity, chemicals, etc.	13
Unknown	11
Maladjustment/misalignment	8
Other	16

TABLE 2.3. Systems and Components Subject to Aging-Induced Failures Resulting In Loss of Function of Unit

Systems and Components	Percentage of Aging-Related Failures	
Instruments and Control Systems	26	
Governor		12
Control Air System		3
Wiring and Terminations		2
Sensors		2
Fuel System	15	
Engine Piping		7
Injector Pumps		5
Injectors and Nozzles		2
Starting System	10	
Starting Air Valve		5
Controls		2
Starting Motor		2
Cooling System	10	
Piping		3
Pumps		2
Heat Exchangers		2
Engine Structure	9	
Crankcase		3
Cylinder Liners		2
Main Bearings		2
Other Systems	30	

TABLE 2.4. Causes of Aging-Related Failures that Result in Loss of Function or Reliability

Failure Cause	Percentage of Aging-Related Failures
Adverse conditions - vibration, shock	32
Poor manufacture or construction quality control	23
Adverse environment - dust, humidity, etc	15
Human error - maintenance, operation	9
Poor design - wrong application or component	7
Other	15

The instruments and control system appeared to be the most vulnerable to failure in all categories. Within both this specific system and for all systems considered, the governor was the single component most subject to failure from all causes. The control air system, wiring, terminations, and sensors appeared to exhibit a significantly high failure rate, but considerably below that of the governor.

The analysis indicated that, for all systems and components, the primary causes of failure could be grouped into vibration, thermal and physical shock, and other adverse conditions. In this group, vibration loosening was the primary mechanism of degradation. Vibration and vibration loosening were also major matters of concern for the instrument and control system.

The fuel system was found to be second in aging-related degradation. Engine piping, injector pumps, and injectors experienced the most failures. The most prevalent degradation mechanism was vibration loosening. For the injector pumps, failure mechanisms were distributed between poor manufacture/construction, vibration, and environmental influences.

The third system most afflicted by aging degradation was the starting system with the air admittance valves, controls, and starting motors being the most troublesome components. Adverse environmental conditions were identified as the principal cause. Poor system design also appeared to be a major contributor to failure. These findings indicated that, in general, these systems may be designed without sufficient consideration for potential degradation due to moisture intrusion with subsequent corrosion, fouling, and other damage.

In the study, cooling systems were found to experience aging degradation of piping, pumps, and heat exchangers. While pump and pump failures were caused principally by vibration loosening of fasteners, the causes of heat exchanger failure were distributed between vibration, environmental factors, and manufacturing/construction quality. Vibration damage to heat exchangers was generally caused by loose internal components.

The fifth most cited system in the aging study was the engine structure. Components found prone to aging failures included the crankcase, cylinder liners, and main bearings. Crankcase failures were due to vibration and improper operation. Cylinder liner failures were associated with poor manufacturing/construction, thermal stresses, and design problems, while the main bearing failures were caused by oil contamination, poor maintenance, and design. These failures tended to occur early in the service life and declined to less importance after five years of operation.

2.2.2 Aging Trends

An analysis of the data base to determine trends in aging related failures as plants become older is summarized in Figure 2.1. This figure shows the not unexpected fact that as plants grow older, the percentage of failures from aging increases. The percentage of aging failures appears to increase from about 45% the first year of plant commercial operation, at which time the diesel generators might have had several years of testing and operation, to about 65% in the 15th year. This does not imply that the numbers of failures are increasing, only that the aging related fraction is larger.

To put Figure 2.1 in the proper perspective, it should be noted that the numbers of failures decline continuously with increasing plant age. This is due to two factors, less failures per plant and fewer plants in each increasing age group. Another point to be made is the effect of better

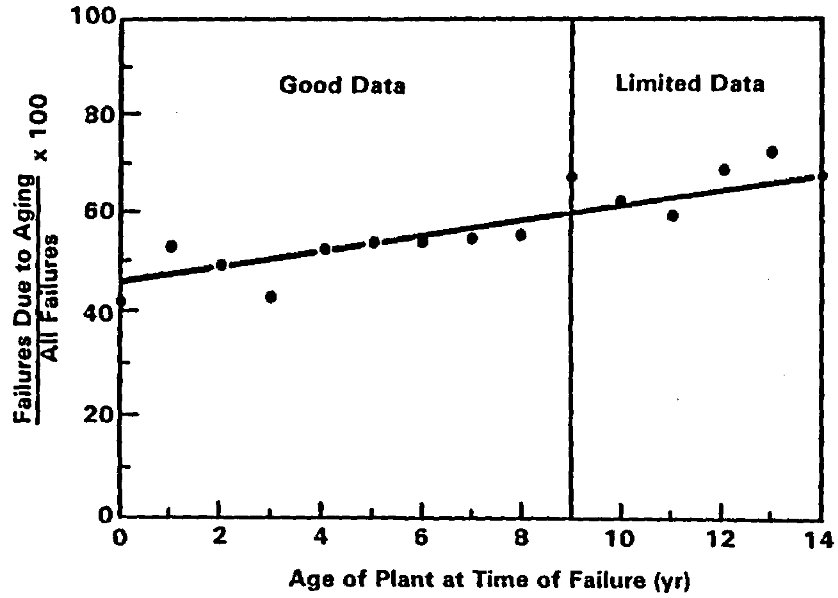

FIGURE 2.1. Percent of Failures Due to Aging

operational and maintenance performance in reducing diesel generator failures. If plants could somehow reduce all failures due to human errors, faulty new components, and similar causes then the only expected failure causes remaining would be time-dependent degradation and wearout failures. In this case, the aging trend would go to 100%. This operational and maintenance improvement appears to be happening in the plants, thus, the increase in the percentage of failures due to aging.

The analysis of the data indicates that the percentage of aging failures due to vibration, adverse environment, and overstressing from unanticipated conditions stays relatively constant. Some components exhibit an early "burn-in" period during which they exhibit an increased aging failure rate, while others experience an increased aging failure rate as they become older. For example, the following components seems to exhibit a decrease in aging failures after 5 years of operation:

- instrument and control system relays
- fuel system piping on engine
- starting air valve
- lubricating system heat exchangers
- lubricating oil
- crankcase

- pistons
- breakers.

The aging failure percentage rate of the following components increases slightly or remains constant after 5 years of operation:

- governor
- injector pumps
- coolant pumps
- cooling system piping
- starting system controls
- starting motors
- lube oil pumps
- turbochargers
- electric generator
- switchgear relays.

A general review of the aging failure data indicates that manufacturing, construction, and poor design problems tend to be reconciled early. Time independent causes of aging failure tend to be maintenance, operation, and maladjustment/misalignment induced degradation. Time-dependent causes of aging failure tend to be adverse operating conditions (e.g., vibration and shock) and adverse environmental conditions (e.g., dust, chemical exposure, etc.). It may be assumed that the change of the overall failure rate appears as shown in Figure 2.2. Here the total failure rate exhibits an early "burn-in" period where the early problems from design, manufacturing and construction are discovered and resolved, thereby increasing the system's reliability. After these problems are resolved, the time dependent failure rate stays relatively constant over a relatively long period. Finally, as exposure to adverse operating and environmental conditions increases, the time-dependent failure rate should increase. Evidence of general wearout has not been detected.

2.2.3 Correction of Aging-Induced Failures

Actions employed to correct the aging-related failures reported in the data base are summarized in Table 2.5. This table shows that 78% of the aging failures were corrected by replacement of the aged part or by some form of maintenance such as realignment or readjustment. The types of corrective actions performed on the components most susceptible to aging are summarized in Table 2.6.

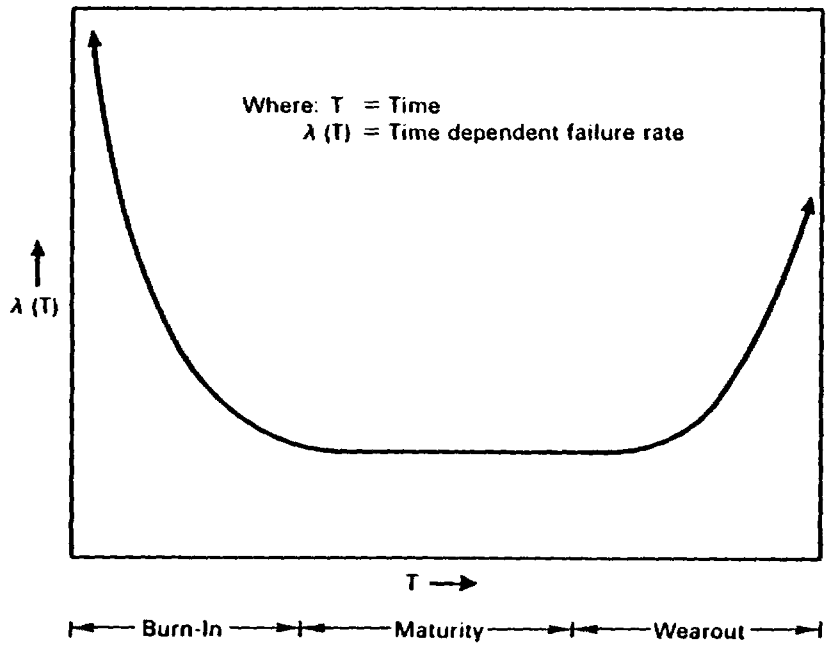

FIGURE 2.2. Change in Failure Rate Over Time

TABLE 2.5. Summary of Most Frequent Corrective Actions for Aging Failures

Corrective Action	Action Code	Percent of Aging-Related Failures
Replacement - same type of component	rs	52
Maintenance - realignment or adjustment	m	26
Replacement - new or upgraded component	rn	13
Repair - welding or replacement	r	5
Enhanced preventive maintenance	pm	2
Redesign	d	1

Only cylinder liners, pistons, starting air valves and cooling system heat exchangers were identified as needing replacement by new or upgraded parts when an aging failure was encountered. The remaining systems and components were repaired by replacement with a similar part, adjustment, or repair of the failed part. Secondary corrective actions included improved maintenance training, preventive maintenance, and improved management procedures. These secondary corrective actions appeared to enhance the primary

TABLE 2.6. Corrective Actions for Components Most Susceptible to Aging

System	Component	Action Code
Instrumentation and Controls	Governor	rs,m
Fuel System	Injector Pumps	m,rs,pm
	Piping on Engine	m,rs
Starting System	Controls	m,rn,pm
	Starting Air Valve	m,rn,pm
	Starting Motors	rs,pm
Cooling System	Pumps	rs
	Piping	rs
	Heat Exchangers	rs,mr
Lubricating System	Pumps	rs
	Heat Exchangers	rs
Intake and Exhaust	Turbocharger	rs,pm
Engine Structure	Crankcase	rs
	Cylinder Liners	m,rn

action. For example, the secondary corrective action for vibration loosening was, generally, enhanced preventive maintenance, which, of course, would tend to prevent the recurrence of the original failure.

2.3 STRESSORS

The statistical analysis of the failure data base resulted in the identification and ranking of the stressors identified in Table 2.4 that can lead to the failure of diesel-generator components. Another valuable ranking of these stressors and their relative importance was obtained from an industry-wide workshop on diesel generator aging held under the auspices of the NPAR Program (Hoopingarner 1987, Vol. 2). Attending were representatives of U.S. utilities, vendors, contractors, consultants, and the national laboratories. One of the principal objectives of this workshop was to obtain the industry's perception of issues and problems regarding nuclear service diesel generators and to identify potential solutions.

The workshop attendees identified essentially the same aging stressors as found in the statistical analysis of the data base and summarized in Table 2.4. However, they ranked them in a somewhat different order of importance as shown in Table 2.7. This table suggests that the principal stressors leading to the aging of diesel generator components are environmentally related. The second, third and fourth most important stressors were, in order, maintenance practices, testing practices, and operating practices. Additional important stressors were identified which included vibration, fuel/lubricant degradation, and gasket/seal degradation. It was apparent from the expressed concern about aging degradation factors such as vibration, fuel/lubricant degradation, gasket degradation, and environmental stressors such as dust, water, and heat, the workshop participants perceived that deterioration of diesel generator systems to be relatively influenced by their normal operating environment.

TABLE 2.7. Workshop Participant's View of Major Aging Stressors

Rank	Major Stressors
1.	Environmentally induced - dust, water, heat, oil, chemical, etc.
2.	Maintenance errors - inadequate training, etc.
3.	Fast starts and other regulatory induced factors
4.	Design inadequacy - wrong application, or poor component
5.	Operation induced - inadequate training and skills
6.	Vibration induced
7.	Fuel or lubricant degeneration
8.	Gasket, seal, or organic material degeneration
9.	Inadequate spares - quality, storage, ordering problems, data and specifications
10.	Corrosion
11.	Thermal stress
12.	Manufacturing or quality problems
13.	Fatigue not related to vibration
14.	Others

The workshop participants identified several additional aging stressors not identified or adequately emphasized earlier in the statistical analyses. These included 1) periodic testing procedures that overstressed engine components and related systems by imposing frequent cold, fast starts to verify operational readiness, 2) operational and maintenance inattention caused by the infrequent operation of the units and the highly formalized maintenance procedures for safety-related nuclear plant components, and 3) the absence of any plant or industry-wide trending/failure analysis practices to identify failing components before they actually fail. Fully 60% of the workshop participants identified trending/failure analysis as the recommended method to ameliorate aging failures in emergency diesel generators.

2.4 SUMMARY OF NPAR STUDY CONCLUSIONS AND RECOMMENDATIONS

The NPAR Diesel Generator Phase I Study identified the system components most susceptible to aging failure, and these components are summarized in Table 2.3. It also identified the stressors listed in Tables 2.4 and 2.7 as those most important in causing these failures. Based on Phase I results, other input provided by the industry, and new Phase II research, it was concluded that a significant reduction of aging effects can be achieved and a long-term improvement of diesel-generator system reliability can be obtained. The key to this reduction of aging effects and reliability improvement is 1) the reduction in the fast-start stressor imposed by current regulations, 2) the implementation of new recommended testing and trending procedures and 3) improved maintenance practices. To provide this key, a new program is recommended that would integrate testing, inspection, monitoring, trending, modification, personnel training and maintenance. The new recommended program is further described in Section 5.0. The more important elements of the new proposed program are discussed in the following paragraphs.

2.4.1 Improved Diesel Generator Testing

To eliminate the fast-start testing stressor that was perceived by the industry representatives as one of the major causes of diesel-generator aging failures, it was recommended that the presently required fast-start, statistically-based testing methodology be replaced with an alternate testing procedure requiring slower starting and loading procedures used commonly in non-emergency power applications.

Diesel experts consulted during the NPAR Phase II research provided recommendations regarding improved testing procedures to obtain data on about 30 operating variables that would provide the necessary information to establish engine/generator conditions (Hoopingarner et al. 1988). They also evaluated slow-start, slow-load testing in comparison to current fast-start and load procedures and concluded that the slower starts would adequately test all important system components. One possible exception is the load sequencing relays which, alternatively, could be electrically and electronically tested using commonly available plant testing equipment to ensure proper operation.

A correctly managed monthly testing program involving slow starting and loading would induce little aging effects in the emergency diesel-generator. By contrast, the current fast starting and loading testing requirements can produce substantial harm and significant aging effects through the production of large mechanical and thermal stresses, inadequate lubrication during initial acceleration, high rotating and sliding pressures, overspeeding, etc. During this monthly slow starting and loading testing program, adequate data should be collected for key engine operating parameters that could indicate degrading performance or an impending component failure. For many important components such a program could then detect approaching performance failure and allow orderly repair long before the current testing procedure could induce the actual failure. Monitoring and trending will not be able to detect all degraded performance, of course, but the deterioration that will be detected is significant. These recommended tests will be presented and discussed in Section 5.2.

2.4.2 Condition Monitoring and Trending

The diesel experts further recommended that some of the more important data developed in the operational surveillance testing described in Section 2.4.1 be monitored and trends established to show the possible presence of long-term component or system degradation. This should detect many potential component/system failures before the system actually fails. By anticipating these failures and providing timely repair/maintenance, cost and safety benefits would accrue from the avoidance of both equipment damage and unscheduled downtime. From the monetary standpoint alone, the payback period from such a monitoring and trending program could be less than a year, based on non-nuclear service experience.

In contrast, the present testing program performed according to Regulatory Guide 1.108 is a reactive process; it provides chiefly statistical information on the ability of the unit to start and assume the prescribed load. However, it provides no assurance regarding future engine operability. The engine status as indicated by this approach can be shown to lag true engine condition by a year or more. Preliminary analysis by Monte Carlo methods shows that statistically one could expect to detect a 6% step change with only a 60% probability in a 50 test series.

2.4.3 Maintenance Training, and Inspection

Several recommendations were developed regarding maintenance procedures and training. One important recommendation is that teardown of the diesel engines solely for the purpose of inspection be avoided unless there is a definite indication that its operation is degraded or there is an impending component failure based on performance data trends. Analyses of failure data have also been performed by the U.S. Navy and the airline industry which show a definite average, short-term, adverse effect of such teardowns on the engine reliability.

It was also recommended that licensee maintenance organizations should not treat engine governors as "black boxes" which are often left alone until a failure occurs. These governors were shown to be a major cause of engine failure and must have regular and careful inspection, adjustment, and preventive maintenance based on a firm understanding of its mechanism and service needs.

This understanding of the governor, as well as the engine/generator, must be developed by providing the maintenance staff with adequate training and motivation. The staff associated with each plant should be given training equivalent to that offered by the specific engine and governor manufacturer that supplied the engines for that plant. Further, the personnel should be provided with failure fault diagrams with defined corrective actions for both maintenance and operation of the units. These troubleshooting aids should list information on the most common causes of failure to start and run along with a sequence of corrective actions. The availability of such information in a real plant emergency speeds up the process of restarting the engines, when the failed component and problems are relatively minor in nature.

Finally, it was recommended that engine inspections and preventive maintenance be increased to mitigate the aging and wear results of the vibration stressor. This maintenance should focus on the engine or instrumentation mounted on the engine or the engine skid. Normal engine vibrations have a known and severe influence on control system instruments and their calibration. Vibration cannot be eliminated, but its effects can be ameliorated by keeping fasteners/fittings tight and by frequently recalibrating instrumentation subject to this vibration.

3.0 THE EMERGENCY DIESEL GENERATOR MISSION AND DESIGN FEATURES

U.S. nuclear power plants are required to have both onsite and offsite sources of emergency electrical power to assure that the plant can be shutdown without endangering public health and safety. In almost all plants, the onsite source of emergency power is provided by redundant diesel generators which are called upon to supply power upon loss of the off-site sources. The capacity and capability of either the onsite or offsite sources is required to be sufficient to assure that 1) the nuclear fuel design limits and design conditions of the reactor coolant pressure boundary are not exceeded as a result of anticipated operational occurrences and 2) the core is cooled and containment integrity and other vital functions are maintained in the event of postulated accidents.

The design of the onsite emergency power system is governed by Regulatory Guide 1.9 which references the requirements of The Institute of Electrical and Electronics Engineers, Inc. (IEEE) Standard 387-1977.

3.1 MISSION ANALYSIS

The redundant diesel generators supplying emergency power are connected to one of two or more redundant Class IE electrical power distribution systems supplying equipment capable of placing the plant in a safe shutdown condition following an accident accompanied by a loss of off-site power. Each emergency generator is capable of automatically starting and accelerating to rated speed, and subsequent loading of all engineered safety features and essential shutdown loads, in the required sequence, within the minimum time intervals established by the plant's safety analysis. They are designed to be capable of continuous operation at rated load, voltage, and frequency until manually stopped or automatically tripped. Generally, the diesel generators are started up if any engineered safety system is triggered regardless of the availability of offsite emergency power. If the power from the offsite emergency buses is interrupted or degraded, the equipment loads associated with each Class IE distribution system are sequentially connected such that the voltage will not fall to less than 75% of rated voltage and frequency will not be less than 95% of rated frequency. Generally, the diesel generators are started and accelerated to full speed in approximately 10 seconds and fully loaded within 1 minute if a loss of offsite power accompanies the triggering of safety systems. If there is no loss of off-site power, the emergency diesel generators are operated continuously to maintain readiness. Under this condition, other auxiliary equipment may be connected manually through administrative procedures to the emergency buses up to the capacity of the emergency generators. This loading is especially important with port-scavenged two-cycle diesel engines which cannot be run unloaded for long periods of time without the buildup of combustion product deposits which can threaten their continued availability.

The diesel engines used for nuclear service emergency power are very large and are the type commonly used in ship propulsion and stationary power applications. For these uses the engines are started and partially loaded and then thoroughly warmed up before the application of full load, and operated continuously for extended periods. With this type of service, they have proved to be very long lived and dependable. In nuclear emergency power application, the conditions of service differ appreciably, and the stressors developed by this service can lead to accelerated aging. The more important stressors include the following:

1. The engine is required to accelerate rapidly, producing maximum piston ring-cylinder wall forces and bearing forces at a time when normal lubricant films have not been completely formed. The resulting metal-to-metal contact can result in cylinder wall and cam surface scuffing and accelerated main bearing and connecting rod bearing wear.

2. The rapid acceleration can produce amplified crankshaft torsional vibration as the crankshaft rapidly encounters successive harmonics of its natural frequency without opportunity for damping from normal mechanisms. This amplification was thought to cause the observed crankshaft cracking in some Enterprise engines which were not equipped with torsional vibration dampers. Amplified torsional vibration may also occur in other components such as the engine-driven water pumps and the camshaft and gears.

3. The rapid acceleration and loading of the engines without allowing for thermal equilibration can lead to high mechanical and thermal stresses in the cylinder block and crankcase that can cause distortions of the engine structures. These distortions can, in turn, lead to metal-to-metal contact (scuffing) and accelerated wear of components. Such scuffing may also be a source of very high temperature and subsequent crankcase explosions.

4. Following the rapid acceleration to speed, an overspeed condition occurs as the governor acts to gain control of the engine rpm. This overspeed condition can result in increased stresses in engine and generator components that can accelerate mechanical wear and loosen generator wiring.

5. The turbocharger overspeeds immediately after rapid engine acceleration which could enhance wear, especially since the turbocharger bearing lubrication is not completely established at this time.

6. The brief periods of operation between long standby periods provide opportunity for bacterial growth and degeneration of the fuel and lubricants. Water from condensation or small leaks may also contaminate the lube-oil system. Condensation can contaminate the fuel oil, which typically stays in the tanks for years because of low use factors. Longer periods of operation help both of these problems.

Stressors associated with fast-starting and loading in response to accident signals are certainly important. However, because of their frequency, the most important stressors are those associated with the periodic fast-start testing mandated by regulations that simulate the starting and loading sequence that would be encountered during an emergency. Real emergency (unplanned) fast starts amount to only 2% of all starts, and the rest are tests (EPRI 1987). Of the unplanned starts, only about one-half was followed by loading. On the average, there are only 5 incidents involving loss-of-offsite-power in the U.S. per year (EPRI 1987).

Testing programs and other guidelines for the diesel generators are currently defined by Regulatory Guides 1.9, 1.108 and 1.137 and include:

- capability qualification tests
- start and load acceptance qualification tests
- margin tests
- preoperational tests
- availability and proper function tests (performed to verify that safety-related loads do not exceed the emergency generator rating and that each unit is suitable for starting, accepting and supplying the required loads)
- monthly availability tests performed while the reactor is in operation (fast starting with assumption of load up to the nameplate rating). If failures are experienced, test frequency requirements could be dramatically accelerated as described in Section 1.1.

The role of the diesel generator safety mission related to the aging study has been reviewed with the following results. To respond to a large-break LOCA event with a corresponding loss of all offsite power, a diesel generator needs to start promptly and deliver its full emergency loads until the emergency is over. This mission profile is the basis and focus of current regulatory requirements and testing. For small-break LOCA events with a loss of offsite power, the related needs for emergency electrical power and the diesel mission profile are much less stringent. In this case, the need for power is extended to about 5 minutes or so and the emergency power level needs are reduced, but the time duration for emergency power may remain for several days.

With over 1000 reactor years of operation in U.S. regulatory history without a large-break LOCA event for primary water containment and with the recent criterion 4 (leak-before-break) rulemaking, it may be concluded that the true mission envelope for the diesel-generator may be redefined with consequential benefits. The most realistic mission envelope appears to be:

- total duration - 2 to 3 days
- diesel start and load time - within 5 minutes

- power level - less than calculated full load (core and containment sprays not needed). Also, by usual design practice, less than the engine nameplate rating by a conservative margin.

3.1.2 Related Mission Studies

The 10- to 12-second starting time imposed by the typical plant Technical Specification is the result of 10 CFR 50, Appendix A, requirements which mandate a conservative approach to mitigating a large-break loss of coolant accident (LOCA) with a coincident loss-of-offsite-power. Recently, the NRC outlined a new, more realistic, approach for performing LOCA analyses. Under sponsorship of the Nuclear Safety Analysis Center (NSAC), studies were performed by General Electric (Muralidharan 1986) and Westinghouse (Schwarz 1988) to investigate the implications of this more realistic analysis and calculation method for the emergency diesel generator starting time.

Both studies revealed that considerable relaxation of the approximately 10-second starting time requirements may be possible. The results of the General Electric study indicated that the start time could be increased to 118 seconds in a typical BWR/6 without the peak fuel temperatures exceeding the 2200°F limit imposed by 10 CFR 50, Appendix K, for a combined LOCA and loss-of-offsite-power. In the Westinghouse study, it was shown that the start time could be increased to 53 seconds in a typical Westinghouse four-loop plant without exceeding this 2200°F peak cladding temperature limit. However, for starting times greater than about 45 seconds, containment temperatures may exceed limits for in-containment safety equipment making this the effective emergency diesel generator starting time limitation for Westinghouse plants.

The effect of extended emergency diesel generator start time on certain non-LOCA accident scenarios was also investigated by Westinghouse. These non-LOCA accidents include 1) steam system piping failure, 2) feedwater system piping failure, and 3) loss of power to station auxiliaries. In these accident scenarios, the emergency diesel generators must provide power to the safety injection pumps and/or to the auxiliary feedwater pumps. It was concluded that the delay of power to the safety injection pumps accompanying a 45-second emergency diesel generator start time was acceptable. However, it was also concluded that a similar delay of power to the auxiliary feedwater pumps would cause auxiliary feedwater to be delivered later than assumed in currently accepted licensing calculations and, therefore, may cause a reduction of existing margins. The amount of margin reduction was not quantified in the Westinghouse report.

A similar investigation of the effect of non-LOCA accidents was not included in the General Electric study.

3.2 RECOMMENDED EMERGENCY POWER MISSION PROFILE

The operating envelope of conditions for diesel-generators should address testing conditions, non-LOCA emergency power conditions, and LOCA centered conditions. The testing profile and conditions are discussed in paragraph 5.1 and will not be addressed here. The recommended emergency power mission then may be reduced to a design envelope of conditions and a more realistic envelope of the most probable requirements for emergency power.

At this time, LOCA-related rulemaking has not reduced requirements for emergency power, equipment qualification, and some other issues that appear to be closely related to the LOCA design requirements. Therefore, it is recommended that present design requirements and large-break LOCA operating conditions be retained for qualification purposes. But, as discussed in the mission analysis and for aging concerns, there is little justification to continue with the routine testing of this equipment for fast-starting and rapid-loading capabilities associated with the large-break LOCA conditions and requirements.

The most probable risk-responsive requirements for the diesel-generator mission are very high reliability with the durability to produce power over 3 to 4 days until the emergency passes and the reactor cooling requirements rapidly drop off. This is essentially the "station blackout" issue. But, accepting this mission envelope for the diesel-generator system also results in the reduction in aging degradation of many important engine components through less harmful test requirements. Several diesel experts have been consulted for assurance that a gradual engine start and load sequence does, indeed, test adequately for the mission requirements. A properly structured test program will test reliability and durability much more appropriately than current requirements outlined in Regulatory Guide 1.108. Aging issues and concerns are also addressed in an appropriately structured test program, and the envelope of design and operational requirements may also be checked with reduced aging and wear effects.

The conservative diesel-generator mission profile, which should be the basis for testing and for setting certain engine control components, is recommended to be established as follows:

- Reliability
  - very high, greater than 0.95 for each engine
- Duration
  - three to four days appears adequate
- Start Time
  - design and qualification, 45 seconds maximum
  - routine testing for reliability verification, within 1 minute should be acceptable, but 30 seconds is an acceptable compromise with conservative margins
  - other testing--no requirements

- Start and Load Time
  - for design and qualification, 105 seconds maximum (BWRs)
  - for design and qualification, 45 seconds maximum (PWRs)
  - for routine testing, rapid loading should be avoided. (recommended gradual loading over a minimum time of 5 minutes)
  - for six months or outage testing, same as design and qualification time [if General Design Criterion No. 4 (leak-before-break) is further relaxed to include emergency power fast-starts may be eliminated].

3.3 RECENT RELATED NRC REGULATORY ACTIONS

Unresolved Safety Issue, USI A-44, "Station Blackout," has been resolved by the issuance of the Station Blackout Rule (10 CFR 50.63) and Regulatory Guide 1.155, "Station Blackout," released in August 1988. Section 1.2 of RG 1.155 establishes the need for a reliability program. This is directly related to, and supported by, the findings of the aging research for a need for an improved aging mitigation program. Aging mitigation actions improve reliability and thus, in reality, the two programs have common needs and corrective actions.

Generic Issue B-56, "Diesel Reliability" is currently in an advanced stage of the resolution process. Again, the reliability focus will result in resolution features and recommendations similar to the findings of the aging mitigation research. Release of proposed Regulatory Guide 1.9, Revision 3 is expected to resolve this issue.

4.0 MAINTENANCE ISSUES

Emergency diesel generators in nuclear service already exhibit excellent reliability. In a recent survey of U.S. of the reliability of diesel generator in U.S. nuclear plants, it was reported that the failure rate was only 1.4% for both testing and planned demands, and 2.2% for unplanned demands between 1983 and 1985 (Wyckoff 1986 and Nuclear Engineering International 1987). During these years, there were 0.075 losses of diesel generator power per site-year of all durations and only 0.023 losses per site-year that were longer than 30 minutes. On the basis of these data, it was concluded by EPRI and the Nuclear Safety Analysis Center (NSAC) that there is little opportunity for improvement. However, the consequences of a total loss of emergency diesel generator power, during certain reactor design events, is so unacceptable from the standpoint of public health and safety, that available and reasonable methods to further improve reliability cannot be ignored.

In addition to the reduction of aging stressors as discussed in Section 3.0, another avenue available to enhance emergency diesel generator reliability and to mitigate aging is to employ a more focused maintenance program. Cost-effective maintenance attention on the EDG units before failures occur will improve their availability. In addressing maintenance issues, it is useful to first examine maintenance/reliability programs in other applications.

4.1 MAINTENANCE/RELIABILITY STUDIES

Studies of maintenance/reliability practices used in airline and military systems were examined to determine the essential features of each. Specific studies examined were performed by United Airlines (Noland 1978) on aircraft power plants and the Department of Defense (Prichard 1984) on military shipboard systems. The concern in both of these studies was the development of an age-reliability analysis methodology and data that would support decisions on whether to overhaul machinery or equipment at predetermined intervals.

On the basis of large amounts of data on the failure rates of many complex systems and components, it was possible in both studies to categorize aging, expressed as the variation of the probability of failure with time, into seven different types illustrated in Figure 4.1.

The Type IV failure probability behavior suggests that the failure rate may remain constant indefinitely and that overhaul of the equipment will do nothing to improve the failure rate. In this case, it would, of course, be inappropriate to overhaul the equipment at any time unless it suffers damage or its performance deteriorates. The Type VI behavior indicates early "wear-in" or "infant mortality" followed by a stable failure rate. Infant mortality is the price often paid for overhauling equipment, and, in such cases, there is little or no reliability benefit obtained from an overhaul. In reality, the type VI failure rate curve is closely related to the type I failure rate curve and perhaps represents the first part of the type I

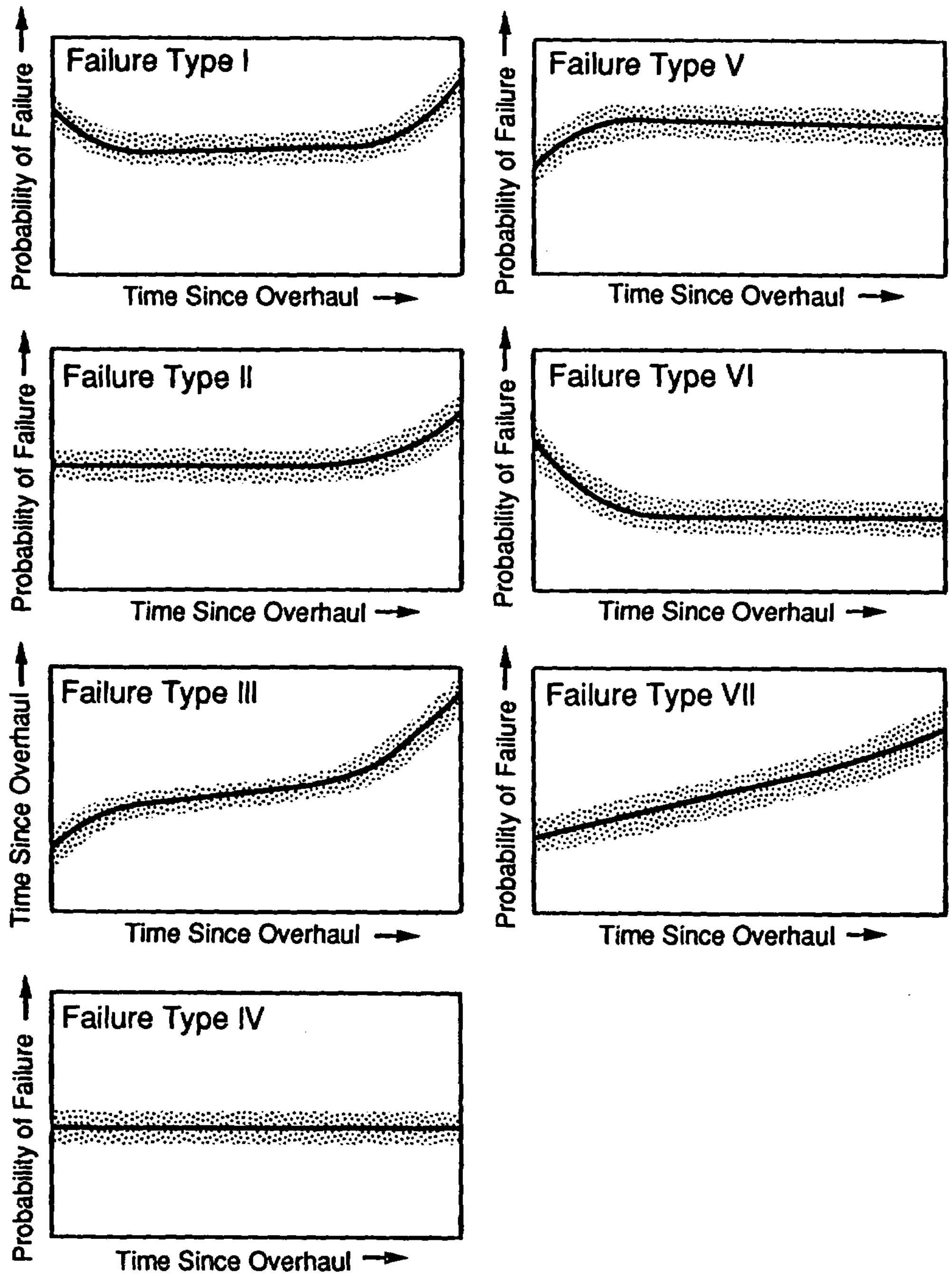

FIGURE 4.1. Types of Failure Behavior Observed in Age-Reliability Studies

diagram. Type II, Type III, and Type VII behavior are the "classical" wear-out patterns showing definite increases of the failure probability especially when the equipment exceeds a certain age. This equipment will benefit from an overhaul without the penalty of infant mortality. However, the total fraction of equipment involved in these failure types ranges from 7 to 18% in the two studies. Thus, the "classical" equipment percentage is much less than anticipated by most knowledgeable people. Type V behavior shows a pronounced increase in failure rate followed by a steady failure rate. Overhaul of this equipment would be beneficial, but it is problematical if the improved failure behavior is worth the cost. The other failure behaviors shown in Figure 4.1 are combinations of the above basic behavior patterns. For these cases, some benefit in failure rate can be obtained, but it will require careful timing to assure that the overhaul is to be cost effective. With Type I behavior, timing is especially important because benefits from avoiding "wear-out" behavior is counteracted by the "infant-mortality" behavior.

The results of the Department of Defense and United Airlines studies have established the percentage of systems, subsystems and equipment items exhibiting these seven types of failure behavior for a large data base of shipboard and aircraft propulsion failures. These results are summarized in Table 4.1.

The results shown in Table 4.1 show the important fact that, in 73% of the equipment surveyed in the Navy study and 82% of the equipment considered in the United Airlines study, Type IV and VI behavior was observed and routine overhauls would not be beneficial over the time period studied. For an additional 9% of the equipment in the Navy study, and 7% in the United Airline study, overhaul was found to be of only transitory benefit (Type V) and of questionable value. Clearly, for only 18% of the equipment in the Navy study, overhauls were necessary to maintain a reasonably low failure rate (Types II and III). For about 30%, it could actually be harmful. Only 11% or less of the equipment in the United Airlines studies could benefit from routine overhaul.

The basic conclusion of both studies was that a purely time-based maintenance, at fixed overhaul periods, is ineffective in improving reliability of equipment and can actually cause more trouble than it cures. In fact, Prichard (1984) concluded that, without any available performance data for a specific piece of equipment, an equipment manager would be more often right than wrong in deciding not to overhaul it. Noland (1979) argued that systematic diagnostic monitoring of equipment performance would provide more information of developing deterioration and would enable the application of timely maintenance and overhaul such that overall reliability could be

TABLE 4.1. Results of Equipment Age-Reliability Analyses

Failure Type	Navy Study	United Airlines
I	0%	4%
II	14%	2%
III	4%	0%
IV	41%	14%
V	9%	7%
VI	32%	68%
VII	0%	5%

enhanced. He also argued for a closer liaison between maintenance and design engineers in the identification of persistent deterioration problems so that the design engineers can more effectively engage in product improvement.

4.2 IMPLICATIONS FOR NUCLEAR SERVICE EMERGENCY DIESEL GENERATORS

Nuclear service emergency diesel generator systems consist of thousands of components. The percentages of components having the types of failure patterns identified in the Navy and United Airlines studies have not been determined, but should not differ substantially from the experience of the referenced research. If the results of these studies are extrapolated to nuclear service diesel generators, it can be concluded that through time-based maintenance there is less than a 20% chance of improving the overall failure rate, even for a short time. This conclusion is further supported by the results of the Navy study on shipboard emergency diesels. Although these units are generally smaller than nuclear plant diesel generators, the components and subsystems are similar, and they can be expected to behave similarly. The Navy study indicated that these emergency diesels, on an overall basis, exhibited a Type IV failure pattern indicating that little improvement in the failure rate could be expected from a time-based maintenance program alone. The study indicated, however, that with Type IV behavior, improvements may be obtainable through long-term monitoring and trending. Therefore, a similar reliability benefit should occur for nuclear plant emergency diesel generators through a well planned and executed trending and reliability program.

This conclusion was arrived at independently by PNL's diesel generator experts who also recommended a program of diagnostic monitoring and trending to ensure diesel generator reliability. The details of their recommended program will be described and discussed in Section 6.

4.3 MAINTENANCE/REGULATORY ISSUES

Monthly testing for statistical information performed according to Regulatory Guide 1.108 with failure reporting is a reactive process with no assurance of future operability. A good overall program of testing, monitoring and trending, on the other hand, is an active process that can detect many incipient failures before a component or system actually fails. Therefore, it provides a method by which emergency diesel generator reliability and availability can be effectively increased.

To take advantage of the potential benefits of an improved testing, monitoring, and trending program on diesel generator reliability, it is recommended that regulatory attention on the overview requirements should be reviewed. Each utility should outline their overall emergency diesel generator operation, test and maintenance program and especially their revised inspection, monitoring, and trending activities. This regulatory attention should include methods proposed by the licensee to establish normal, degraded, and unsatisfactory performance for the EDG system.

5.0 RECOMMENDED DIESEL GENERATOR PROGRAM

This section presents a recommended diesel generator management program that integrates testing, inspection, monitoring, trending and maintenance activities. It was developed for the purpose of enhancing the reliability of nuclear service diesel generators by a group of diesel engine experts working with PNL's NPAR staff in a workshop reported by Hoopingarner et al. (1988).

The recommended program is similar to programs already successfully used by many small utilities that depend on diesel generators as a source of base-load or peaking power. It was developed with the intent of 1) reducing the aging stressors associated with present regulatory test requirements while providing enhanced confidence in the diesel generator's capability to respond to accident situations, 2) providing information to identify potentially failing systems and components to allow their timely replacement/repair before a failure actually occurs, and 3) enhancing the utilities' response to potential or actual failures of diesel generator components or subsystems.

The key elements of the recommended plan are as follows:

- Testing Monitoring and Trending - The approach of monthly testing should be changed from the current regulatory approach requiring fast starting and loading to a new approach that would allow slower starting and would enable the acquisition of surveillance information. This new approach would eliminate the fast-start aging stressor identified in Section 3.0 and would result in obtaining operating data on key engine performance parameters as recommended by studies described in Section 4.0. These parameters could be monitored and trended to either 1) ensure normal performance or 2) reveal future engine problems. The recommended program of testing, monitoring, and trending is described in detail in Section 5.1.

- Inspection Program - If not already performed by a licensee, a program of weekly, monthly, quarterly, and annual inspections should be undertaken to assure that the effects of operating and environmental stressors are detected and repairs effected before they have time to cause a more serious condition or failure. The principal focus of these inspections should be on systems and components identified in the Diesel Generator Aging Research program (Hoopingarner, et al. 1987). This inspection program is described in Section 5.2.

- Maintenance Program - A maintenance program responsive to the testing, monitoring, and trending program should be undertaken. Teardowns of a satisfactorily performing engine simply for the purpose of inspection should be avoided unless the monitoring and trending program indicates unacceptable degradation of a system or component performance. Spare qualified parts and components should be on hand to facilitate frequent or impending repairs predicted by the trending activities. The maintenance program should include frequent calibration and servicing of instrumentation mounted on the engine skid. The recommended maintenance program is described in Section 5.3.

- Personnel Training - Training programs should reenforce the onsite maintenance capability for systems and components identified as the most susceptible to aging degradation with particular emphasis on 1) the engine governor and the instrument and control system. Plant personnel should be trained in the use of monitoring and trending in the identification of required maintenance. Maintenance supervisory staff should be provided with failure fault diagrams with defined corrective actions to enhance maintenance response speed to malfunctions, especially if they should occur during a real plant emergency. This training program is described in Section 5.4.

- System Modifications - The implementation of the above features may require the installation and calibration of some sensors. These will vary from engine-to-engine depending on the manufacturer and details of the installation. These gages and sensors do not need to be safety-grade equipment and need to be only local read-out types, such as dial-type pressure gages. The failure of these gages will not typically lead to engine failure, especially with the usual presence of plant operators. Modifications are further described in Section 5.5.

5.1 TESTING, MONITORING AND TRENDING

Section 1 of this report discussed the basis for the diesel generator testing requirements of Regulatory Guide 1.108. The requirements had the original purpose of assuring diesel generator availability by routine testing under accident conditions accompanied by a loss of offsite power as determined by very conservative criteria defined in 10 CFR 50, Appendix K. The starting and loading times required varied from plant-to-plant, but typically were 10 to 12 seconds starting time and 30 to 45 seconds to full load.

Recent operating experience and research results discussed in Section 2 have suggested that fast starting and loading during this testing has a deleterious effect on engine reliability and can actually result in some engine component failures. Furthermore, studies performed by EPRI and others discussed in Section 3 have indicated that the fast starting and loading requirement mandated by 10 CFR 50, Appendix K is overly conservative. Instead, these studies indicate that the emergency power requirement is of the order of 1 to 2 minutes for a loss of coolant accident accompanied by a loss-of-offsite-power and 5 minutes, or more, for a loss-of-offsite-power occurring alone.

5.1.1 Recommended Periodic Testing and Monitoring Procedure

It is recommended that the primary purpose of monthly testing should be changed to a new approach of surveillance testing. The purpose of the monthly surveillance testing should be to obtain data on key engine performance parameters that indicate the trends in component and subsystem condition. These performance parameters will provide both short-term and long-term trended information on degraded performance which can be a precursor for component or subsystem failure. For each engine manufacturer and installation, the licensee should be required to establish an overall testing and monitoring system that identifies these key parameters and indicators. A suggested list of parameters of interest for this purpose is presented in Appendix A.

The monthly engine testing should follow the guidelines listed below:

1. The engine should be slow started following the manufacturer's recommended procedures and loaded to avoid the fast-start stressor. Good practice is to prelube the engine, open the indicator cocks and roll the engine with the fuel rack in the off position and look for signs of water which would indicate coolant leakage into a cylinder. If no leakage is indicated, the indicator cocks may be closed and the engine may be started normally. Following starting, it should be allowed to idle for about 5 minutes at either a low RPM, which is not close to any crankshaft critical speed, or at synchronous speed. During this time, key engine parameters should be recorded and the engine checked for unusual noises or noise levels. The idle time for two cycle, port scavenged, engines should be limited to 10 minutes to avoid the possibility of exhaust manifold fires. The engine should then be brought up to speed and fully loaded over a period of 10 minutes or more to allow the pistons and liners to expand at the same rate and, thereby, reduce wear on these components. During acceleration through the engine's critical speeds, acceleration should be swift, but not at maximum acceleration, i.e., at less than full fuel rack setting. For regulatory purposes, full engine test load should be defined as the plant design emergency load which is, generally, 70% to 90% of the engine nameplate rating.

2. It is recommended that the test run time should be between 12 and 14 hours and spread over three working shifts to provide the opportunity for plant personnel to gain familiarity with the sounds of a properly operating engine and operating procedures. Three sets of data should be collected at 1-hour intervals, or more, during the run period. Due to fuel oil storage requirements and other plant-specific conditions, the recommended run time may not be entirely practical at all plants. For these situations, the run time should be until temperature stability occurs, about one hour, and the operational data (Appendix A parameters) should be obtained in two periods at least one-half hour apart.

3. The diesel generators should be started approximately 2 hours before the end of a work shift. After the full engine test load is achieved and the engine temperatures stabilize, the first set of performance data should be collected by the shift personnel starting the engine. Another set of data should be collected at 1 to 4 hour intervals; at least one set should be obtained by each shift.

4. A detailed, written, test procedure and data sheets should be used. The data sheets should indicate maximum and minimum allowable values for each significant performance parameter recorded. Data from previous tests should be readily available for comparison purposes. If any parameters fall outside of the acceptable range, the cause should be determined by engineering/maintenance staff and the test discontinued, if the conditions threatens the integrity of the engine.

5. The test program should be scheduled so that within a few months each shift has the opportunity to start and load the engine. This will provide an opportunity for all assigned staff to start the engine or to observe a start. Alternatively, the engine could be unloaded, shutdown and restarted each shift during the test to provide this opportunity. These extra starts will not add to aging concerns when properly performed on a prelubed and thermally stable engine.

6. Routine monitoring and trending of the diesel engine base vibrations and diesel start time may be performed. However, it is important to understand that normal variations in these parameters are extremely large and can be misleading. Other operational parameters are more indicative of engine conditions and should be relied upon instead. These comments do not apply to generator vibration which should be measured and monitored.

7. Data collection, recording, and instrument calibration processes and procedures should follow the plant's quality assurance requirements for surveillance of similar safety equipment.

The slow-starting procedure recommended above is typical of the way that large diesel engines are started by small utilities that use diesels for base-load or peaking-power applications. In these applications, it is not unusual to achieve over 100,000 hours of operation in the 35 to 50 year lifetime of an engine even with daily or more frequent starting and stopping. It is not unexpected to achieve 20,000 hours or more between major overhauls. Therefore, the starting procedure recommended for these surveillance tests will not introduce any unusual aging stressors. However, if an engine has not been fast-started by a reactor emergency response signal in a 6-month period, it should be fast-start tested in similar fashion as currently performed to check that the control circuits operate within acceptable limits.

An alternate method of fast-starting and loading the engine which eliminates some of the fast-start stressors is as follows:

- Emergency start the engine to determine if it starts in the prescribed time (10 to 12 seconds) without load.
- Allow engine to idle for 5 minutes.
- Shut down the engine, then immediately restart it, using the fast-start system. Note: the engine start time and then the time to full load to determine if the engine reached full load within the required time period after starting.

This alternate fast-starting procedure will allow oil films and proper lubrication to be established before load is applied and, therefore, reduce wear. It should also verify the engine's ability to start and take load within the prescribed times.

5.1.2 Other Periodic Monitoring

It is recommended that certain aging-related parameters and data should be collected on a quarterly basis and during plant outages. Fuel oil, lubricating oil, and cooling water analysis should be done quarterly and the results monitored and trended so that aging mitigation measures and action can be undertaken. Crankshaft deflection tests should be performed during the refueling outage and the 110% load test performed. During this overload test, all data listed in Appendix A should be recorded, but the principal data of interest are cooling and lubrication system performance parameters, turbocharger temperatures, and cylinder temperatures.

5.1.3 Testing After Specific Faults and Maintenance

The present general practice is to fast start an engine after a malfunction and/or any significant maintenance to ensure engine operability. Because of aging concerns, this practice is not recommended. Other tests or requalification measures may be superior to this practice. For example, malfunctions attributable to human error or a clearly defined fault should require the specific correction for the error or fault and an appropriate component test at most. Maintenance on a specific engine system or component should require a subsystem or component test to ensure operability. In both examples, the engine should not be started or tested because engine operability is adequately ensured by the less severe test procedure.

In cases of major engine rebuilding where highly stressed moving components are replaced (e.g., crankshaft, connected rods and other components where metal fatigue is a concern or has previously incurred) the engine should be operated for 3×10^6 stress cycles at design loads before the engine is returned to full operational status. This number of stress cycles is generally accepted as sufficient to demonstrate high cycle fatigue resistance in ferritic steels (PNL 1985). A load cycle is assumed to be one revolution for a 2-cycle engine and two revolutions for a 4-cycle engine.

Engine cylinder liners, gear trains, bearings and, generally, pistons should not be considered to be highly stressed and should not be subjected to such stress cycle testing.

5.1.4 Trending of Performance Parameters

Without parameter trending, data monitoring would have little predictive value to the licensees and the NRC. The practice of trending involves the plotting of the data obtained for selected performance parameters obtained during the testing and monitoring activity versus total engine operating hours. (Note that trending involves only the variable engine parameters listed in Appendix A. Load and governor settings, for example, are not parameters that need to be trended, but they need to be held uniform from test-to-test and carefully recorded for each test.) Data plots should be retained over the lifetime of the diesel generator unit. To predict failure, or the time at which performance of the engine, component or subsystem reaches unacceptable limits, it is necessary to only consult these plots and observe the rate at which the curves through the data points approach limiting values for each parameter. For some parameters, as discussed earlier, data taken from test-to-test will continuously trend to these limiting values, and, for others, the data values will remain constant over a long period of time, only to degrade rapidly at the end of life. An example of the latter is the lifetime performance of a bearing. For this case, bearing temperature and oil pressure will remain virtually constant over long periods; however, near the end of life, bearing temperature will rise rapidly and oil pressure will drop. Unfortunately, the temperature rise may be very quick and progress from about normal to abnormal and failure may occur in a matter of hours. Fortunately filter deposits in the lube-oil system, oil analysis and other techniques are available to more directly detect bearing wear.

A key element of effectively using performance data trends to predict equipment failure is the prior establishment of limiting values for each parameter. It is recommended that these values be established for each diesel generator unit by the licensee using information from the engine and generator manufacturer. Fortunately, experience with diesel engines applications and electrical generation equipment spans many decades, and acceptable and unacceptable operation is well understood and recognized. Therefore, the process of establishing limits on operating parameters should be quite straightforward. Another point is not all parameters need to be trended nor do they need to be trended over the entire range of values. For example, an oil pressure may start out at a value and would be expected to eventually drop to some minimum acceptable value. Trending may be deferred until the oil pressure drops to less than 50% of the acceptable operating range.

5.2 INSPECTION

It is conventional practice that diesel engines used for marine and non-nuclear stationary power applications receive weekly, monthly and outage inspections, each with different goals. When these engines were adapted for nuclear plant emergency power application, fewer inspections were assumed to be required. It was perceived that this service required fewer operating hours and was less rigorous than conventional engine service. However, it has been found in the aging research program that nuclear emergency power service is, in reality, severe service, and a more complete inspection program could be extremely effective in mitigating aging problems and enhancing start and run reliability. Therefore, a comprehensive inspection program involving weekly, monthly, quarterly, and annual inspection is recommended. This inspection program is described in the following sections.

These inspections should be performed by the same personnel who have preventative maintenance responsibility for the diesel generators. The yearly outage inspection team should include a manufacturer's representative or a diesel consultant in addition to plant personnel. All inspections should follow a prepared checklist and should be performed according to the plant's quality assurance program.

5.2.1 Weekly Inspections

In general, weekly inspections include day and shift inspections and should follow the good practice standards for conventional diesel generator systems and the manufacturers recommendations. The inspecting personnel should check for oil and water leaks, signs of vibration-induced loosening of fasteners, and environmental stressor conditions identified in the aging research (Hoopingarner et al. 1987). Such stressors collectively account for over 40% of diesel generator failures observed. In addition, the engine governor and associated linkage should be lubricated and checked for free operation. Other items to be included in weekly inspection program are as follows:

- The engine oil/water keep-warm system should be checked for correct operation and temperature settings.
- Lubricating oil levels should be checked in the engine, governor, turbocharger and outboard bearing, as applicable. Also check for water in the oil.
- The engine prelube system should be checked for correct oil level and pressure, as applicable.
- Engine cooling water inventory and cooling system valve settings should be checked.
- The air start system should be checked for air pressure, presence of moisture downstream of the dryers, and valve settings.
- Breaker and relay status should be checked, especially following maintenance periods.

5.2.2 Monthly and Quarterly Inspections

The monthly and quarterly inspections should concentrate on systems, subsystems and components identified in the diesel generator aging research program as being particularly susceptible to aging such as the governor and the instrument and control system. The power train and generator units need less attention since they are much less susceptible to aging-related failures than other engine components.

Monthly inspections should include, but not be limited to, the following items:

- Check filters and louvers in the combustion air and diesel room cooling air systems.
- Check the position of the fuel oil duplex filter manual valve to assure that the fuel is being directed through one filter with the other held in reserve.
- Check for vibration loosening of fasteners or vibration induced damage. Should be done while the engine is operating for best results.
- When a lubricating oil filter is changed, sample the surface and cut open the filter and visually examine it for unusual contamination or wear particles.
- With the engine running, check the engine and associated subsystems for oil or water leaks, and check for exhaust leaks.
- With engine running under load, check diesel exhaust smoke color or take smoke meter reading.

The monthly inspection should also include the weekly inspection items and can replace one weekly inspection.

Quarterly inspections should include the following items:

- Clean and inspect the strainers and filters in the starting air system.
- Sample the fuel oil in the storage and day tanks for 1) gum or jelly formation and 2) bacterial growth at any water condensate fuel oil interfaces.
- Sample the lubricating oil and analyze for wear particles, water contamination, and oxidation.
- Inspect the fuel oil filters and replace at the recommended frequency or as shown by station procedures.

- Inspect the combustion air and exhaust manifolds, especially in two-cycle engines, for oil and carbon deposits that could constitute a fire hazard.
- Inspect relay enclosures and control cabinets for dust and dirt and clear where necessary.
- With the engine operating, visually check all skid-mounted equipment for vibration loosening and damage, especially valve operators, instruments, equipment mounts, and tube and pipe fittings.
- Check instrument and control settings and perform tests of any components in this system that have been prone to failure or deterioration, as shown by plant records.
- Check governor oil level, overspeed governor setting and governor performance in controlling speed and frequency.

These monthly and quarterly inspections probably have the most value if scheduled to follow closely the monthly start-run test. Signs of vibration-induced loosening and problems associated with the environmental stressors may be detected before they have time to progress to a more serious condition or to failure.

5.3 MAINTENANCE

A preventative maintenance program should be coupled with the inspection program recommended in Section 5.2 to discover and correct problems before they threaten the reliability of the diesel generator. Program attention should be principally directed at the important identified aging stressors and equipment particularly susceptible to these stressors. For example, vibration was the stressor identified to cause the highest percentage failure in diesel generator aging studies (Hoopingarner et al. 1987). Preventative maintenance should focus on aging and wear effects of this stressor and emphasize calibration, repair, and replacement of skid-mounted instrumentation, because of its potential sensitivity to this vibration.

One piece of equipment that should be given particular attention in the preventative maintenance program is the governor, because its failure is a major cause of engine unavailability. Governors must have regular and careful maintenance, adjustment, and preventative maintenance based on a firm understanding of the governor and its service needs.

It is recommended that the spare parts inventory for each installation be given careful consideration to assure that adequate spare parts are on hand to allow rapid repair/replacement of those parts that the trending program identifies as requiring frequent attention. With an ample parts inventory on hand, failures or approaching failure can be dealt with expeditiously.

Finally, it is strongly recommended that an engine not be torn down solely for the purpose of inspection, unless the monitoring and trending program provides evidence of an internal malfunction or impending malfunction. It was indicated earlier that such disassembly could actually detract from engine reliability. This should not be interpreted to imply that engine components or subsystems with a known qualified lifetime should be operated beyond this lifetime, simply because monitoring and trending shows no difficulties. However, such positive monitoring and trending results should be considered by the regulatory staff to, perhaps, justify a longer qualified lifetime for the component or subsystem.

5.4 TRAINING

It is recommended that a minimum of two persons for each nuclear unit be given maintenance training equivalent to that offered by diesel engine and governor manufacturers for their customers. Such persons should be at the appropriate working level; these persons should be used to train other personnel.

Additional training should be given all maintenance personnel on those components and systems most susceptible to aging failure and on the effects of the identified stressors for aging. The governor and instrumentation and control system should be given particular attention in the training program.

The development and use of failure/fault diagrams by licensees is also recommended. These diagrams are trouble-shooting aids which list the most common causes of each specific malfunction, such as failure to start, and a recommended sequence of inspections and corrective actions to correct the malfunction. The availability of such information could conceivably permit the recovery and starting a malfunctioning engine in a real plant emergency within several minutes. Training would be required to implement this recommendation.

5.5 MODIFICATIONS

Many diesel generators in nuclear plants have already been equipped with pre-lube and keep-warm systems to mitigate the wear and aging effects of fast-start testing. It is recommended that any engines which have not been so equipped should be provided with these systems. In addition, a method of using the auxiliary pump or other equipment should be developed to assist the lubrication of the upper crankshaft assembly of opposed piston engines before planned or test starts. Such a system would reduce wear and aging of this assembly. Other engine types would also benefit from this practice for valve deck lubrication and various other components such as the turbocharger that are not presently receiving adequate lubrication during the fast starting and loading time period.

To avoid aging influence of vibration on the skid mounted instrumentation and controls, it is recommended that they be moved to another location not subject to vibration where this is practical. This will avoid one of the most important stressors to the instrument and control system and could result in a substantial increase in the overall reliability of the diesel generator.

6.0 NPAR PROGRAM DEVELOPMENT RECOMMENDATIONS

The integrated program of testing, monitoring, trending, inspection and training described in this report is complex and would benefit from a pilot development program implemented with the cooperation of industry at one or more nuclear power units. The objectives of this program are: 1) to create a program that will serve as a guide to all utilities in the development of their own effective and regulation-compliant program, 2) provide NRC with the background information on the implementation and control of such a program, 3) develop data on the benefits of this program on diesel generator reliability, and 4) provide preliminary cost-benefit data for industry motivation. It is recommended that this work involve an independent organization which can provide required technical supervision, evaluation of the results, statistical analyses, cost/benefit studies, and comparisons with the reliability of similar diesel generators in other plants not fully compliant with the provisions of this program.

The work may be performed in 5 tasks as follows:

- Task 1--Program Implementation - This task should provide the groundwork for the implementation of the testing, surveillance, and trending activities. It will include the development of
  - testing procedures
  - lists of specific monitoring data to be acquired
  - definition of acceptable ranges of monitored data
  - data sheets and recording procedures
  - trending procedures.
- Task 2--Equipment Modifications - Review the installation of any instrumentation needed for the implementation of the monitoring program developed in Task 1 on the diesel generator to be studied. Implement other equipment modifications recommended in this report as necessary. Such equipment modifications are anticipated to be minimal. Present diesel-generator installations have most of the necessary instrumentation already in place.
- Task 3--Training of Personnel - In this task, plant personnel should be trained in the performance of the testing, monitoring, and trending program developed in Task 1. Maintenance personnel should be given other maintenance training as recommended in this document.

- Task 4--Monitoring and Trending - The program developed in Task 1 should be performed over a period of less than 1 year. Modifications to procedures, data acquisition methods, and items will be made as the need is identified to streamline the program and to achieve maximum benefits.

- Task 5--Data Analysis and Reporting - Maintenance activities and failure rates experienced during the period of study should be analyzed to determine reliability improvements and projected cost savings of this program. These results will be reported to the NRC and industry by means of periodic technical reports, topical reports, and journal articles.

It is anticipated that the above program could be completed within one year to obtain valid results, after cooperation agreements and other preliminary actions are completed. If results are desired on a faster schedule, accelerated testing could be accomplished by a more frequent engine start-run and monitoring schedule during the implementation period only.

6.1 OTHER DEVELOPMENTAL ACTIVITIES

It is recommended that a program be undertaken to develop the necessary hardware and software to analyze the status of the diesel generator control system and to report its status to operating personnel. These systems should, continuously or on demand, 1) determine the status of the engine emergency start circuits, unloaders, sequencers, relays, contacts, and all wiring and 2) provide a warning signal to test/operations personnel in case of a possible malfunction or fault. The development of such a system is not necessary for the implementation of the recommended testing, monitoring and trending program; however, its availability will provide an enhanced state of diesel generator reliability, since it will enable plant staff to determine the state of availability of this system without subjecting the diesel generator to the aging stressors associated with fast start and run tests now performed to provide this information. Along with this development, regulatory requirements must be reevaluated and revised to take advantage of this benefit.

7.0 RECOMMENDED REGULATORY IMPLEMENTATION

The NPAR aging study was originally intended to develop data and recommendations for NRC consideration related to potential safety problems caused by the aging process. The general application of this study was extended in Phase II to use the diesel research information for 1) diesel reliability improvement, 2) plant technical specification modification, 3) improvement of resource application by the NRC and the utilities, and 4) development of specific recommendations to change some regulatory requirements. All of these end uses of the research have been accomplished or are under active consideration. Collectively, the safety implications of these changes and recommendations are important.

7.1 REGULATORY GUIDES

Current regulatory guides and requirements for fast-start testing, fast engine loading, and overload testing are being reconsidered by the NRC. In association with certain nuclear plant technical specifications, these current guides and requirements may lead to greater future safety problems and unreliability. Regulatory guide requirements for routine testing have been redefined to include slow-start testing, slower engine loading, and diesel overload testing objectives that can be supported by the study results. Nuclear Regulatory Guide 1.108 addressing diesel-generator testing requirements will be withdrawn and combined into a new single Regulatory Guide 1.9, "Selection, Design, Qualification, Testing, and Reliability of Diesel Generator Units Used As Onsite Electric Power Systems at Nuclear Power Plants." Diesel Statistical probabilities, especially statistics based on 100 valid start and run tests, are very difficult to defend on a technical basis due to the very long time period needed to collect the data (maybe 5 years). A better regulatory approach is a monthly operational readiness test ("health checkup") of the diesel generator system. This concept has been included in the 1989 draft of Regulatory Guide 1.9. This draft is supported by the research results.

Regulatory Guide 1.137, Fuel-Oil Systems For Standby Diesel Generators, has not been revised since October 1979. Aging considerations for the system and the fuel oil contents needs to be addressed. The scope of the changes should include the following important aging related considerations:

- The licensees should be encouraged to operate the engines and thus use and replace oil. Reasonable regulatory guidelines to match Regulatory Guide 1.9 recommendations need to be developed to meet this objective. For older plants especially, this could include the relaxation of oil-on-hand guidelines to 3 to 4 days minimum. With modern transport possibilities, especially heavy-lift helicopters, this is reasonable.

- The recommended tank lining materials need to be defined better.

- For common cause failure considerations, tank and equipment redundancy needs to be addressed.

- A few other details need to be addressed to conform to revised Regulatory Guide 1.9 and proposed technical specification guidelines.

7.2 TECHNICAL SPECIFICATIONS

The plant standard technical specifications related to the diesel-generator system should be modified to add to safety assurance. The research information gathered in the NPAR Diesel program confirms opinions developed by industry and regulatory personnel over many years of experience that current technical specifications are not always conservative nor effective. In particular, those related to fast engine starting and loading, frequent sensor calibration, engine startup during abnormal plant conditions, frequent starts and special test requirements need to be carefully evaluated. This process has been started by the NRC staff.

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APPENDIX A

RECOMMENDED DIESEL GENERATOR MONTHLY TEST PARAMETERS

APPENDIX A

RECOMMENDED DIESEL GENERATOR MONTHLY TEST PARAMETERS

General Data

Date of test
Time of test
Ambient air temperature
Barometric pressure
Relative humidity (if convenient)
Total hours on engine (hour meter)
Governor setting (manual or automatic)
kW/load
Volts
Kilovars

Parameter General Data Required	Primary Use of Data
Generator Data (Alternator)	
Alternator winding temperature(s)	1. Evaluate condition of windings 2. Detect loss of cooling capacity
Alternator bearing temperature (One or two bearings) (Oil temperature)	1. Detect bearing problems
Engine Cooling Water	
Water pressure to engine	1. Ensure engine operability (mission safety) 2. Detect plugged jacket water system 3. Check pump condition
Or Water temperature to and from engine (water pressure at these same points also checks these conditions)	1. Monitor control valve operation 2. Monitor heat exchanger performance 3. Higher engine load will increase temperature difference
Or Water temperature to and from engine water cooler (could be radiator)	1. Monitor heat exchanger fouling 2. Detect incorrect control valve operation
Water temperature to and from raw water cooler	1. Monitor fouling 2. Water pump operation
Water temperature to and from turbocharger (where water cooled). Exhaust gas ΔP and ΔT may also be used.	1. Fouling and water flow of turbocharger 2. Monitor turbocharger loading
Water temperature to and from turbocharger after cooler	1. Monitor cooler fouling
Water pressure and temperature to and from L.O. cooler	1. Monitor cooler fouling

Parameter General Data Required	Primary Use of Data
Lubricating Oil	
Oil pressure to engine	1. Ensure engine operability 2. Detect filter plugging 3. Troubleshooting for regulating valve, engine wear 4. Detect incorrect oil, viscosity too low or high
Oil temperature to and from engine (oil sump temperature)	1. Detect fouling of heat exchanger 2. Monitor control valve operation 3. Detect low oil flow
Oil pressure to and from L.O. filter	1. Detect filter element plugging 2. Detect damaged elements (low delta p)
Oil temperature to and from L.O. cooler	1. Detect fouling 2. Monitor control valve operation
Oil pressure to turbocharger	1. Detect incorrect pressure regulating valve setting 2. Ensure engine operability
Oil temperature to and from turbocharger	1. Monitor turbocharger bearings
Air to Engine	
Ambient air temperature, barometric pressure and relative humidity (Note: These are on pave A.1 also.)	1. Needed for monitoring "standard air conditions" for efficiency calculations or trouble-shooting
Air pressure and temperature to turbocharger	1. Turbocharger efficiency calculations
Air pressure to and from after cooler	1. Turbocharger efficiency calculations 2. Air-side cooler fouling detection

Parameter General Data Required	Primary Use of Data
Exhaust	
Exhaust temperature out of each cylinder Cylinder No. 1 Cylinder No. 2 Etc.	1. Monitor fuel injector performance 2. Detect broken rockerarms, worn rings or valve problems 3. Acceptable balance between cylinders
Exhaust temperature to turbocharger turbine (preturbine temperature), more than one thermocouple may be required	1. Turbocharger efficiency 2. Safety to ensure temperature limit to turbocharger is not exceeded
Exhaust temperature from turbine	1. Monitor turbocharger performance and condition
Fuel Oil	
Fuel oil pressure to and from engine filter	1. Detect filter plugging or damage
Fuel oil pressure to and from fuel oil pump	1. Monitor regulating valve adjustment 2. Monitor pump wear
Fuel Pump Rack Setting	
All cylinders	1. Compare to cylinder exhaust temperatures for performance (both should be reasonably even) 2. Monitor cam timing
Miscellaneous Data	
Turbocharger R.P.M.	1. Monitor turbine efficiency 2. Detect fouling of compressor discharge, turbine conditions, or blade fouling 3. Detect poor engine combustion
Crankcase vacuum or pressure	1. Monitor excessive ring blow-by 2. Detect faulty ejector/blower

Parameter General Data Required	Primary Use of Data
Miscellaneous Data (continued)	
Amount of oil added	1. Monitor engine operation, ring wear and valve guide wear
Lubricating oil analysis (quarterly recommended)	1. Detect wear particles 2. Monitor fuel oil dilution
Engine cooling water analysis (quarterly recommended)	1. Detect corrosion products 2. Ensure correct water chemistry
More optional quarterly monitoring could include:	
Firing pressures for each cylinder	1. Information on ring, valve, and combustion conditions when compared to rack position and exhaust temperature.
Fuel oil metering/heat rate	1. 10% degradation in fuel consumption rate is indicative of problems developing such as injector fouling.

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Recent NRC sponsored aging research work on nuclear service diesel generators has resulted in a recommendation that an improved engine management program should be adopted for aging mitigation and reliability improvement. The center of attention should be to ensure diesel-generator operational readiness. This report emphasizes a "healthy engine concept" and recommends parameters to be monitored to determine engine condition. The proposed program and approach recommended in this report represent balanced management where diesel generator testing, inspections, monitoring, trending, training, and maintenance all have appropriate importance.

Fast-starting and fast-loading tests of nuclear service diesels causes very rapid wear of certain engine components. This report documents this aging stressor. Current periodic intrusive maintenance and engine overhaul practices have been found to be less favorable for safety assurance than engine overhauls based on monitoring and trending results or on a need to correct specific engine defects. This report recommends that the periodic overhaul requirements be re-evaluated.

Diesel generator research on aging and wear is sponsored by the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research. The research reported in this report was conducted by Pacific Northwest Laboratory (PNL), which is operated for the Department of Energy by Battelle Memorial Institute.

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